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Koivisto, Matti Juhani; Maule, Petr; Nuno, Edgar; Sørensen, Poul Ejnar; Cutululis, Nicolaos Antonio

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Statistical Analysis of Offshore Wind and other VRE Generation to Estimate the Variability in Future Residual Load

Matti Koivisto, Petr Maule, Edgar Nuño, Poul Sørensen and Nicolaos Cutululis

Technical University of Denmark, Department of Wind Energy, Roskilde, Denmark

E-mail: mkoi@dtu.dk

Abstract. The growing share of variable renewable energy (VRE) sources, which are driven by weather patterns, can cause challenges to the operation and planning of power systems. This paper studies the variability in wind and solar photovoltaic generation in Nordic and Baltic countries. Combined with load time series, the resulting residual load is analysed in 2030 and 2050 scenarios. The correlations between load and VRE generation are studied, and it is shown that a modified 2050 scenario with higher offshore wind and solar generation share shows lower relative residual load variability compared to the 2050 base scenario. The reduction in variability is specifically significant in residual load ramp rates.

1. Introduction

Variable renewable energy (VRE) generation, such as wind and solar power, varies because it is determined by weather conditions. The growing share of VRE generation is thus expected to increase the variability of residual load (electricity load subtracted by VRE generation) in the future. The residual load needs to be met by non-VRE generation sources or imports from other countries. This paper studies variability in offshore wind and other VRE generation in Norway (NO), Denmark (DK), Sweden (SE), Finland (FI), Estonia (EE), Latvia (LV) and Lithuania (LT) until 2050. Combined with load time series, the resulting residual load is analyzed to help in long term power and energy system planning.

Geographical distribution of installations has a significant effect on the variability of aggregate wind generation [1]-[4]. Increasing the geographical spread can decrease the variability of the aggregate generation significantly [3], [4]. Compared to wind, the geographical distribution of solar photovoltaic (PV) generation has a lesser effect on the variability of aggregate generation [5]. However, a mixture of wind and solar PV can be very interesting when considering the variability of aggregate VRE generation, as wind and solar generation tend to be negatively correlated [6].

The effects of geographical distribution and the generation mix of solar and wind generation on residual load depends on the correlations between load and VRE generation. In the studied scenarios, the correlations between load and wind generations are positive, which reduces the residual load standard deviation (SD) compared to having zero correlation. The correlations between load and solar PV generations are negative because high load occurs during winter. However, the ramps in solar generation are positively correlated with load ramps, which lowers the ramp rate SD of residual load.

The base scenario from [7], with around 36 GW of VRE generation in 2030 and 60 GW in 2050 is used as the baseline scenario. Correlations between the different VRE generation types and load are analysed and the effects on the variability of the residual load are presented using four years of historical load data. In addition, the effects of increased offshore wind share, increased geographical distribution



of installations and increased solar generation share are studied, and a modified 2050 scenario is compared to the 2050 base scenario in relation to variability.

2. Time series data used

This section describes the simulated VRE generation data and the load time series used in estimating the residual load in the 2030 and 2050 scenarios in Section 4. The most important statistical characteristics of the data are presented in Section 3. The analyzed countries, with regional splits, are shown in Figure 1.



Figure 1. The analysed countries with regions marked. © EuroGeographics for the administrative boundaries (regions are combined of the EU NUTS classification).

2.1. Simulated VRE generation data

The VRE generation time series are simulated using the CorRES tool developed at DTU Wind Energy. It is based on meteorological data obtained from the mesoscale Weather Research and Forecasting (WRF) model [8]. The simulations are a reanalysis of past weather. The downscaling method presented in [9], [10] has been used. Mesoscale models tend to underestimate the short-term variability in wind speeds, which is especially pronounced in geographically concentrated offshore wind generation [11]. To reach more realistic simulations, stochastic fluctuations are added on top of the mesoscale wind speed data.

From the WRF model, hourly meteorological time series are obtained on a 10 km x 10 km grid that covers the area of interest. This grid of data was used to create wind and solar PV generation time series for the different countries (installations were aggregated to the closest grid points). When available, existing locations were used for wind installations. For offshore, also planned locations were used. For solar PV, installations were assumed to be scattered through the regions. The application of WRF reanalysis data in large-scale wind and solar PV generation simulation has been validated, e.g., in [12], [13]. An example simulation of the 2030 scenario for the meteorological years 2012 to 2015 can be seen in Figure 2.

2.2. Load data

Four years of hourly historical load data (2012 to 2015) for the analysed countries were acquired from Nord Pool [14]. The aggregate load for the studied countries can be seen in Figure 2. A few clearly incorrect data points were fixed by using the data from a previous day of the same type (e.g., working day) at the same hour of the day.

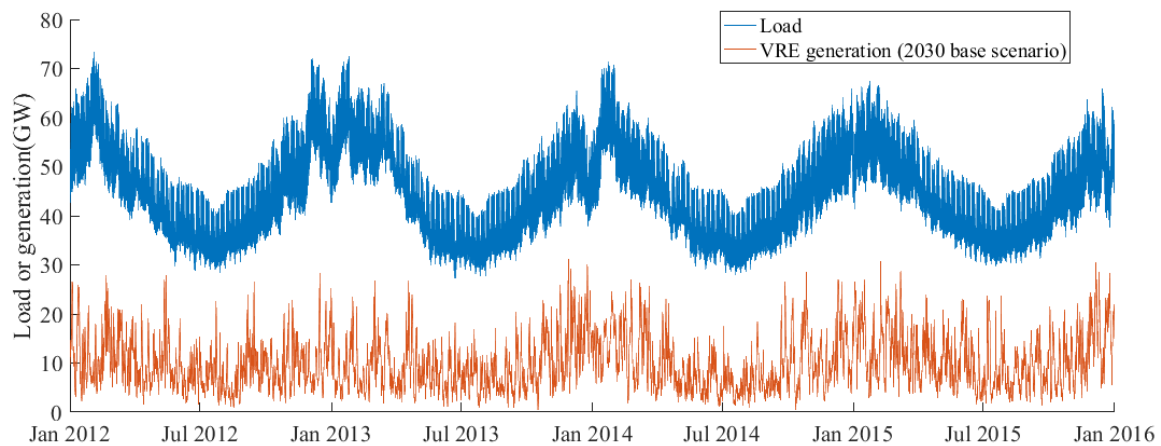


Figure 2. Time series of aggregate load and VRE generation with the 2030 base scenario installations for the four analysed years.

3. Important statistics affecting residual load behaviour

This section describes some of the most important statistical characteristics of the load and VRE generation affecting the behavior of the residual load.

3.1. Correlations between the load time series

Table 1 shows how the load time series of the different countries are correlated. The correlations are generally high; however, countries further away (e.g., DK and FI) have somewhat lower correlations. Because the load time series are highly correlated, the relative standard deviation (RSD), i.e., SD divided by mean of the aggregate load does not reduce much compared to the individual load series. As shown in Table 2, the SD of the aggregate load is 9.01 GW. If all load time series would be fully correlated, the SD of the aggregate would be 9.41 GW; there is thus only about 4 % reduction in the RSD due to loads not being fully correlated.

Table 1. Correlations between the load time series

	DK	EE	FI	LT	LV	NO	SE
DK		0.90	0.76	0.92	0.87	0.73	0.83
EE	0.90		0.90	0.87	0.85	0.87	0.93
FI	0.76	0.90		0.70	0.71	0.93	0.95
LT	0.92	0.87	0.70		0.89	0.62	0.74
LV	0.87	0.85	0.71	0.89		0.65	0.73
NO	0.73	0.87	0.93	0.62	0.65		0.96
SE	0.83	0.93	0.95	0.74	0.73	0.96	

Table 2. Means, SDs and RSDs of the load time series and their aggregate

	DK	EE	FI	LT	LV	NO	SE	Aggregate
Mean (GW)	3.82	0.91	9.42	1.13	0.80	14.6	15.6	46.3
SD (GW)	0.80	0.20	1.52	0.23	0.17	3.12	3.36	9.01
RSD	0.21	0.22	0.16	0.21	0.21	0.21	0.21	0.19

3.2. The load time series first differences

In addition to the load variance, the ramp rate SD of load is important for understating how much load can change from one hour to another (i.e., first difference of an hourly time series). As can be seen in Table 3, the SD of the aggregate load's first difference is 1.59 GW/h. If all load time series first differences would be fully correlated, the SD of the aggregate would be 1.72 GW/h; there is thus about 8 % reduction in the ramp rate SD due to load ramps not being fully correlated.

Table 3. SDs of the load time series and their aggregate's first differences

	DK	EE	FI	LT	LV	NO	SE	Aggregate
SD (GW/h)	0.24	0.05	0.27	0.07	0.05	0.45	0.60	1.59

3.3. Behaviours of different VRE generation types

Basic statistics for the different VRE sources are shown in Appendix B. While SDs are on average higher in offshore than onshore wind generation, the higher mean generation causes the RSD to be on average 8 % lower in offshore than onshore. However, hourly ramp rate SDs are much higher in offshore than in onshore generation. Solar PV has higher RSD than either of the wind generation types.

3.4. Correlations between load and VRE generation

Table 4 shows the average correlations between aggregate load and the different VRE generation types. More detailed data can be seen in Appendix A. Both wind generation types are positively correlated with load, as wind generation is higher in the winter. As expected, solar PV is negatively correlated with load. However, solar generation being negatively correlated with wind generation can still make a case for having solar PV in the VRE generation mix, as will be discussed in Section 4.

Table 4. Average correlations between aggregate load and the different VRE generation types

	Aggregate load	Offshore wind	Onshore wind	Solar PV
Aggregate load		0.12	0.17	-0.11
Offshore wind	0.12		0.36	-0.14
Onshore wind	0.17	0.36		-0.14
Solar PV	-0.11	-0.14	-0.14	

3.5. Correlations between load and VRE generation first differences

It can be seen in Figure 3 that the largest 1-hour changes in the aggregate load (more than 3 GW/h) are almost always associated with a positive 1-hour change in solar PV generation (this is true with the solar generation in most countries). This is because the largest load ramps occur during morning up-ramping, when also the solar PV generation is ramping up. As seen in Table 5, the correlation between solar PV generation and aggregate load is on average 0.36.

Table 5. Average correlations between the first differences of the different VRE generation types and the aggregate load

	Offshore wind	Onshore wind	Solar PV
Correlation with aggregate load's first difference	-0.01	0.00	0.36

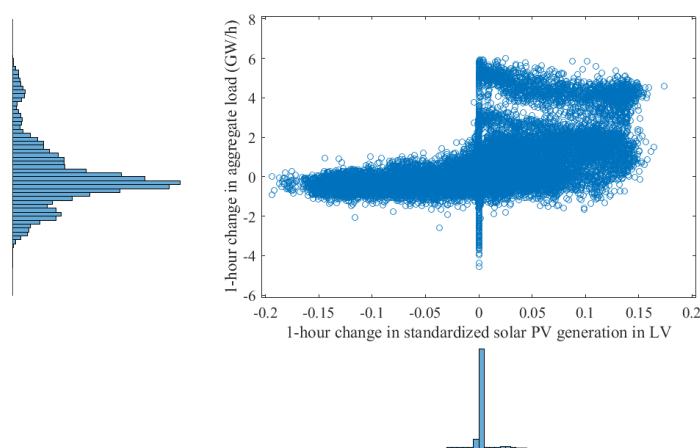


Figure 3. Scatter plot and histograms of the first difference of solar PV generation in Latvia (1 means full installed capacity) and the first difference of the aggregate load (correlation is 0.40).

4. Residual load statistics

This section describes statistics of the estimated residual load for 2030 and 2050 scenarios (assuming load time series remain similar to today). In addition to analyzing the base scenarios, a modified 2050 scenario is presented to show the effects of changing geographical distribution of installations and VRE generation mix to the residual load variability.

4.1. The base scenarios

Figure 4 shows the estimated probability distribution functions (PDFs) of the aggregate load, and the residual loads in the different scenarios. As can be seen in Table 6, the SD of the residual load increases only by a few percentages compared to only load in 2030, but notably in the 2050 base scenario (22 % higher than the SD of load only). As the expected value of the residual load decreases at the same time, the RSD increases very significantly.

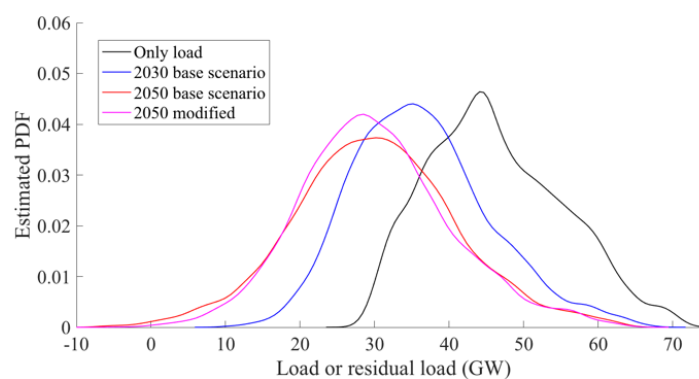


Figure 4. Estimated PDFs of hourly load and residual load in the analysed scenarios (all analysed countries aggregated).

Table 6. Descriptive statistics of residual load in the different scenarios.

Scenario	Mean (GW)	SD (GW)	RSD	5 th percentile (GW)	95 th percentile (GW)
Only load	46.3	9.0	0.19	32.6	62.0
2030 base scenario	36.3	9.2	0.25	22.7	52.9
2050 base scenario	30.1	11.0	0.37	12.3	48.8
2050 modified	30.1	10.2	0.34	14.5	48.3

4.2. The base scenario ramp rates

Figure 5 shows the estimated probability distribution functions (PDFs) of the aggregate load and the residual load ramp rates (first differences) in the different scenarios. Hourly ramp rates in residual load increase only moderately, as can be seen in Table 7: in 2050, the SD of the residual load ramp rate is expected to be 10% higher than in load only.

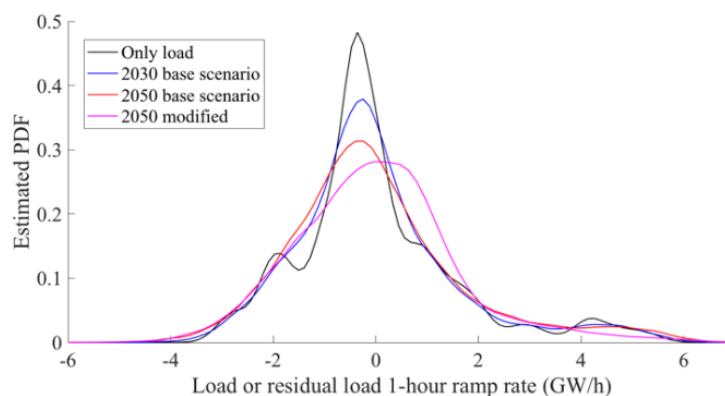


Figure 5. Estimated PDFs of aggregate load's ramp rates, and residual load's ramp rates in the analysed scenarios (all analysed countries aggregated).

Table 7. Descriptive statistics of aggregate load and residual load ramp rates in the different scenarios.

Scenario	Ramp rate SD (GW/h)	5 th percentile (GW/h)	95 th percentile (GW/h)
Only load	1.59	-2.24	3.54
2030 base scenario	1.62	-2.26	3.52
2050 base scenario	1.75	-2.42	3.64
2050 modified	1.57	-2.38	2.87

4.3. The modified 2050 scenario

Modifications were done to the base 2050 scenario to study more the variability of the residual load (the overall expected yearly VRE energy generation was kept constant in all test scenarios). The modifications were twofold: changing the VRE generation mix and the geographical distribution of installations.

Increasing the low offshore wind share in the baseline scenario (9 % of the expected yearly VRE generation in 2050) up to 50 % resulted in a small reduction of the residual load SD (up to 2 %). However, having 100 % of wind offshore increased the SD, and all increases in offshore wind share increased the residual load ramp rate SD. Increasing the overall geographical distribution of wind decreased the residual load SD about 4 % (the shares of wind installations in the different regions can be seen in the 2050 modified data in Appendix B).

The low share of only around 1 % of yearly VRE generation from solar in 2050 was increased to 10 % (with installations mainly in the south). A final modified scenario for 2050, with 30 % of wind offshore, wind installations geographically more dispersed and with solar share of 10 % was created. Detailed installations in the different regions are shown in Appendix B. The overall VRE generation mixes in the different scenarios can be seen in Table 8

Statistics for residual load variability in the modified 2050 scenario are shown in Figures 4 and 5, and in Tables 6 and 7. The modified scenario showed about 7% lower SD in residual load compared to the 2050 base scenario. As can be seen in Table 6, the modified scenario shows a significantly higher 5th percentile value, meaning that very low residual loads are rarer in the modified than in the base 2050 scenario. However, the 95th percentile value is only slightly lower.

As can be seen in Table 7, the modified scenario shows a much lower ramp rate SD compared to the base 2050 scenario. Especially the 95th percentile value is much lower; this can be explained by the increased solar PV share, as solar up-ramping happens often at the same time as load up-ramping (as shown in Figure 3).

However, none of the modifications can alter the fact that during some high load hours of the year there is only little VRE generation available; this causes the right-hand tail of the residual load PDF to reach close to the peak load Figure 4 in all scenarios.

Table 8. Percentages of expected yearly energies coming from the different VRE types in the different scenarios.

	Offshore wind	Onshore wind	Solar PV
2030 base scenario	15%	83%	2%
2050 base scenario	9%	90%	1%
2050 modified	27%	63%	10%

5. Discussion

5.1. Creating more years of load time series

The residual load results presented in Figures 4 and 5, and Tables 6 and 7 are based on four years of hourly data. As such, this does not give reliable estimates of very high or low percentiles; for example, the four years may not include very cold winters, which could cause high residual load hours. In future work, one approach would be to acquire more historical load data; another way would be to build statistical models of the load (e.g., as shown in [15]) in the different countries and use past meteorological data to create simulated load time series for more historical years. VRE generation simulations are available already for 35 past years.

5.2. VRE technology development in the future

The capacity factors shown in Appendix B are based on the today's VRE technologies. In future work, the changes, e.g., in hub heights and specific power will be implemented to model the capacity factors of the future.

5.3. Future work

In addition to the future work discussed in the previous two subsections, an important expansion is to utilize the knowledge of VRE generation variability in the wider context of energy system modelling. For example, if in the future significant flexibility can be obtained from demand-side management, the variability in VRE generation can be better managed. Another example are transmission lines, which are needed to fully utilize the benefits of having VRE generation installations geographically more dispersed. However, transmission lines are expensive, so an analysis of how much interconnection is optimal is needed. Such energy system modelling work is ongoing, utilising the Balmorel energy system model [16] and the VRE generation simulations presented in this paper.

6. Conclusion

The SD of the residual load increases only by a few percentages in 2030 compared to only load, but notably in 2050 (22 % higher than the SD of load only). As the expected value of the residual load decreases at the same time, the RSD increases very significantly. This means that there is less energy to be generated by non-VRE generation types, but with higher needs of flexibility. In the 2030 and 2050 base scenarios, hourly ramp rates in residual load increase only moderately; in 2050, the SD of the ramp rates is expected to be 10% higher than in load only.

Two types of modifications were done to the base 2050 scenario to study more the variability of the residual load: changing the VRE generation mix and the geographical installation distribution.

Increasing the low offshore wind share in the base scenario resulted in a small reduction of the residual load SD. Increasing the overall geographical distribution of wind decreased the residual load SD about 4 %.

A final modified scenario for 2050, with 30 % of wind energy from offshore, wind installations geographically more dispersed and with solar share of 10 % showed about 7% lower SD in residual load compared to the base 2050 scenario. The modified scenario shows a significantly higher 5th percentile value, meaning that very low residual loads are rarer in the modified than in the base 2050 scenario. However, the 95th percentile value is only slightly lower. In the modified scenario, with increased solar generation share, the residual load ramp rate SD is expected to be even slightly lower than in load only. This is due to the positive correlation between solar PV generation ramps and aggregate load ramps.

However, none of the modifications can alter the fact that during some high load hours of the year there is only little VRE generation available; this causes the right-hand tail of the residual load PDF to reach close to the peak load in all analysed scenarios.

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Appendix A: Correlations between aggregate load and the VRE generations

Load	Aggregate	Offshore wind						Onshore wind						Solar PV												
		Dke	Dkw	EE	FI	LT	SE	Dke	Dkw	EE	FI	LT	SE	NMI	NNO	NSY	NVE	SE1	SE2	SE3	SE4					
Offshore wind	Aggregate	0.10	0.15	0.08	0.19	0.08	0.07	0.24	0.13	0.15	0.16	0.11	0.11	0.13	0.10	0.11	0.24	0.37	0.29	0.24	0.21	0.16	0.14	0.14	0.11	
	Dke	0.10								0.82	0.72	0.17	0.07	0.11	0.34	0.30	0.09	0.15	0.26	0.41	0.23	0.05	0.13	0.41	0.72	
	Dkw	0.15	0.73							0.76	0.84	0.23	0.11	0.18	0.32	0.18	0.24	0.42	0.58	0.38	0.06	0.21	0.41	0.55	0.74	
	EE	0.08	0.15	0.21						0.21	0.22	0.82	0.23	0.50	0.52	0.73	0.26	0.18	0.33	0.11	0.15	0.21	0.41	0.55	0.29	
	FI	0.09	0.11	0.18	0.42					0.14	0.17	0.50	0.79	0.85	0.21	0.33	0.38	0.37	0.37	0.07	0.23	0.58	0.61	0.42	0.18	
	LT	0.08	0.34	0.34	0.53	0.26				0.38	0.33	0.52	0.16	0.28	0.86	0.81	0.18	0.28	0.17	0.15	0.13	0.25	0.51	0.47	0.17	
	SE	0.07	0.30	0.33	0.64	0.35	0.80				0.36	0.33	0.63	0.19	0.36	0.74	0.87	0.22	0.16	0.31	0.15	0.17	0.13	0.29	0.56	0.43
	NO	0.24	0.09	0.18	0.18	0.33	0.12	0.17	0.22		0.12	0.18	0.20	0.28	0.30	0.09	0.16	0.75	0.59	0.58	0.19	0.57	0.26	0.34	0.29	0.13
	SE	0.13	0.35	0.43	0.46	0.50	0.41	0.44	0.22		0.45	0.43	0.46	0.33	0.51	0.37	0.47	0.29	0.45	0.20	0.24	0.31	0.63	0.73	0.52	
	Dke	0.15	0.82	0.76	0.21	0.14	0.38	0.36	0.12	0.45		0.87	0.23	0.10	0.16	0.41	0.38	0.13	0.17	0.34	0.48	0.30	0.06	0.19	0.54	0.84
Onshore wind	Dkw	0.16	0.72	0.84	0.22	0.17	0.33	0.33	0.18	0.43	0.87															
	EE	0.11	0.07	0.23	0.82	0.50	0.52	0.63	0.20	0.46	0.23	0.24														
	FI	0.11	0.17	0.23	0.79	0.16	0.19	0.28	0.33	0.40	0.11	0.30														
	LT	0.13	0.18	0.50	0.85	0.28	0.36	0.30	0.51	0.16	0.18	0.61	0.75													
	Fis	0.10	0.34	0.32	0.52	0.21	0.86	0.74	0.09	0.37	0.41	0.35	0.51	0.13	0.25											
	LT	0.11	0.30	0.32	0.73	0.33	0.81	0.87	0.16	0.47	0.38	0.35	0.71	0.19	0.39	0.85										
	NMI	0.24	0.09	0.18	0.26	0.38	0.18	0.22	0.75	0.32	0.13	0.18	0.28	0.31	0.37	0.17	0.24									
	NNO	0.37	0.15	0.24	0.18	0.37	0.16	0.16	0.59	0.29	0.17	0.22	0.19	0.39	0.37	0.15	0.17	0.59								
	NOS	0.29	0.26	0.42	0.33	0.37	0.28	0.31	0.58	0.45	0.34	0.43	0.33	0.28	0.36	0.28	0.34	0.68	0.50							
	NSY	0.24	0.41	0.58	0.11	0.07	0.17	0.15	0.19	0.20	0.48	0.64	0.11	0.06	0.08	0.20	0.18	0.13	0.26	0.38						
Solar PV	NVE	0.21	0.23	0.38	0.15	0.23	0.15	0.17	0.57	0.24	0.30	0.44	0.17	0.19	0.21	0.14	0.18	0.39	0.42	0.58	0.59					
	SE1	0.16	0.06	0.21	0.38	0.13	0.13	0.26	0.31	0.06	0.07	0.25	0.71	0.60	0.11	0.15	0.31	0.41	0.28	0.02	0.13					
	SE2	0.14	0.13	0.21	0.41	0.61	0.25	0.29	0.34	0.63	0.19	0.22	0.42	0.49	0.65	0.24	0.33	0.50	0.41	0.53	0.08	0.23	0.63			
	SE3	0.14	0.41	0.53	0.55	0.42	0.51	0.56	0.29	0.73	0.54	0.56	0.52	0.25	0.45	0.49	0.62	0.39	0.31	0.59	0.23	0.34	0.20	0.53		
	SE4	0.11	0.72	0.74	0.29	0.18	0.47	0.43	0.13	0.52	0.84	0.76	0.28	0.12	0.20	0.49	0.47	0.17	0.21	0.38	0.46	0.27	0.07	0.23	0.69	
	Dke	-0.05	-0.11	-0.15	-0.10	-0.17	-0.08	-0.11	-0.12	-0.09	-0.09	-0.13	-0.11	-0.09	-0.15	-0.11	-0.12	-0.19	-0.14	-0.09	-0.11	-0.14	-0.11	-0.14	-0.12	
	Dkw	-0.06	-0.11	-0.14	-0.15	-0.10	-0.16	-0.08	-0.11	-0.12	-0.10	-0.10	-0.13	-0.11	-0.09	-0.15	-0.11	-0.12	-0.19	-0.15	-0.11	-0.12	-0.14	-0.14	-0.13	
	EE	-0.10	-0.10	-0.14	-0.18	-0.11	-0.19	-0.12	-0.15	-0.09	-0.09	-0.17	-0.11	-0.10	-0.19	-0.14	-0.14	-0.19	-0.17	-0.09	-0.11	-0.14	-0.14	-0.15	-0.11	
	FI	-0.21	-0.09	-0.13	-0.19	-0.16	-0.17	-0.10	-0.16	-0.16	-0.11	-0.11	-0.18	-0.16	-0.15	-0.18	-0.19	-0.23	-0.22	-0.11	-0.16	-0.19	-0.18	-0.13	-0.05	
	Fis	-0.17	-0.10	-0.13	-0.20	-0.14	-0.18	-0.11	-0.14	-0.17	-0.11	-0.11	-0.19	-0.14	-0.15	-0.19	-0.16	-0.16	-0.20	-0.11	-0.14	-0.16	-0.17	-0.18	-0.13	
LT	-0.10	-0.08	-0.11	-0.17	-0.10	-0.17	-0.07	-0.11	-0.14	-0.10	-0.09	-0.14	-0.11	-0.10	-0.18	-0.13	-0.13	-0.18	-0.16	-0.09	-0.11	-0.14	-0.14	-0.15	-0.11	
LV	-0.08	-0.09	-0.13	-0.17	-0.10	-0.19	-0.10	-0.11	-0.14	-0.08	-0.09	-0.15	-0.10	-0.09	-0.18	-0.13	-0.13	-0.19	-0.08	-0.11	-0.14	-0.13	-0.14	-0.10	-0.12	
NMI	-0.10	-0.09	-0.15	-0.19	-0.14	-0.19	-0.11	-0.18	-0.15	-0.09	-0.11	-0.17	-0.13	-0.11	-0.13	-0.18	-0.15	-0.21	-0.23	-0.25	-0.10	-0.16	-0.17	-0.19	-0.18	
NNO	-0.18	-0.08	-0.14	-0.18	-0.16	-0.17	-0.10	-0.19	-0.14	-0.08	-0.08	-0.17	-0.17	-0.15	-0.16	-0.13	-0.22	-0.29	-0.22	-0.10	-0.15	-0.22	-0.20	-0.16	-0.10	
NOS	-0.09	-0.10	-0.16	-0.14	-0.11	-0.16	-0.08	-0.14	-0.14	-0.09	-0.11	-0.13	-0.11	-0.09	-0.14	-0.10	-0.14	-0.22	-0.19	-0.13	-0.16	-0.14	-0.13	-0.16	-0.12	
NSY	-0.07	-0.10	-0.19	-0.13	-0.10	-0.16	-0.09	-0.15	-0.12	-0.08	-0.10	-0.11	-0.10	-0.08	-0.13	-0.09	-0.13	-0.22	-0.19	-0.14	-0.16	-0.13	-0.11	-0.14	-0.11	
NVE	-0.07	-0.10	-0.18	-0.15	-0.12	-0.18	-0.11	-0.18	-0.14	-0.08	-0.10	-0.15	-0.11	-0.10	-0.16	-0.12	-0.17	-0.23	-0.12	-0.17	-0.14	-0.17	-0.14	-0.17	-0.12	
SE1	-0.17	-0.10	-0.15	-0.17	-0.16	-0.18	-0.11	-0.18	-0.15	-0.09	-0.10	-0.16	-0.16	-0.14	-0.17	-0.13	-0.19	-0.27	-0.22	-0.11	-0.16	-0.19	-0.17	-0.17	-0.12	
SE2	-0.14	-0.10	-0.16	-0.17	-0.13	-0.18	-0.11	-0.17	-0.16	-0.10	-0.11	-0.16	-0.13	-0.12	-0.17	-0.13	-0.18	-0.25	-0.21	-0.11	-0.15	-0.16	-0.16	-0.18	-0.12	
SE3	-0.09	-0.11	-0.16	-0.16	-0.11	-0.18	-0.11	-0.13	-0.15	-0.10	-0.11	-0.12	-0.10	-0.12	-0.16	-0.12	-0.14	-0.22	-0.17	-0.11	-0.14	-0.14	-0.17	-0.13	-0.04	
SE4	-0.07	-0.12	-0.15	-0.15	-0.10	-0.18	-0.10	-0.12	-0.14	-0.10	-0.09	-0.14	-0.11	-0.09	-0.16	-0.12	-0.12	-0.20	-0.11	-0.14	-0.11	-0.14	-0.12	-0.15	-0.13	

The colouring is based on how beneficial the correlations are for achieving a lower residual load variance (green means more beneficial); positive correlations between load and VRE generation and negative correlation between the different VRE generation sources are beneficial.

Appendix B: Installed VRE generation capacities in the different scenarios, and basic statistics for the different VRE sources

Scenario	Offshore wind									Onshore wind												Solar PV																							
	DKe	DKw	EE	FI	LT	LV	NO	SE		DKe	DKw	EE	Fin	Fis	LT	LV	NMI	NNO	NOS	NSY	NVE	SE1	SE2	SE3	SE4	DKe	DKw	EE	Fin	Fis	LT	LV	NMI	NNO	NOS	NSY	NVE	SE1	SE2	SE3	SE4				
2030 base scenario	573	1443	250	1206	0	180	0	215		990	4219	635	533	1067	1677	2979	330	5033	124	1410	126	424	5488	4396	1206	268	624	0	0	40	750	2	0	0	0	0	0	0	0	0	0	0	79		
2050 base scenario	573	1443	250	1206	0	180	0	215		1520	6480	400	533	1067	7046	2409	5033	5033	124	1410	126	5488	5488	10975	1206	268	624	0	0	40	740	2	0	0	0	0	0	0	0	0	0	0	79		
2050 modified	1000	2000	1000	1206	1000	950	3000	1500		990	4000	635	2100	1067	1677	2979	2000	5033	124	1410	126	5000	5000	4396	1206	1500	2000	1000	0	1500	1000	1000	0	0	1000	1000	1000	0	0	2000	2000	0	0	2000	2000

The installed capacities are given as MW.

	Offshore wind									Onshore wind												Solar PV																		
	Dke	DKw	EE	FI	LT	LV	NO	SE		Dke	DKw	EE	FI	LT	LV	NMI	NNO	NOS	NSY	NVE	SE1	SE2	SE3	SE4	Dke	DKw	EE	FI	LT	LV	NMI	NNO	NOS	NSY	NVE	SE1	SE2	SE3	SE4	
Mean	0.43	0.45	0.29	0.31	0.35	0.30	0.41	0.34		0.25	0.26	0.26	0.27	0.25	0.24	0.26	0.30	0.35	0.32	0.29	0.23	0.24	0.22	0.27	0.35	0.11	0.12	0.12	0.09	0.09	0.12	0.12	0.10	0.09	0.10	0.10	0.10	0.10	0.11	0.11
SD	0.34	0.31	0.30	0.27	0.32	0.30	0.29	0.26		0.25	0.24	0.24	0.26	0.22	0.24	0.26	0.29	0.25	0.24	0.30	0.25	0.22	0.20	0.22	0.28	0.18	0.18	0.18	0.19	0.14	0.14	0.18	0.15	0.14	0.16	0.16	0.16	0.17	0.17	0.17
RSD	0.77	0.70	1.04	0.88	0.91	1.01	0.71	0.76		1.00	0.95	0.93	0.98	0.87	1.00	1.00	0.95	0.70	0.75	1.03	1.09	0.90	0.89	0.83	0.81	1.54	1.55	1.57	1.64	1.63	1.54	1.54	1.61	1.63	1.60	1.59	1.65	1.61	1.57	1.56
1st difference SD	0.10	0.08	0.11	0.08	0.10	0.10	0.07	0.08		0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.05	0.03	0.02	0.05	0.04	0.03	0.02	0.03	0.04	0.06	0.06	0.06	0.04	0.04	0.06	0.05	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05

The mean and SD values are calculated from the 4 years of data analyzed. As the VRE generation data are standardized (between 0 and 1), the mean values are the capacity factors of the different VRE sources.